INTEGRATED CIRCUITS IN INDUSTRIAL CONTROL*

by Donald Femling and Jack Irwin

ABSTRACT

Applications for the use of integrated circuits (IC's) in place of digital circuits in industrial control equipment increase daily. Several advantages influence the trend; some are indirectly economically advantageous, and some are directly significant from the standpoint of increased speed—an inherent characteristic of IC's.

A Numeric Control Unit to position an x-y table (designed and fabricated by Fairchild Semiconductor) demonstrates the capabilities of IC's in the field of process control. As a beginning, a sequence of design steps were investigated, and alternate solutions evaluated on paper. In the evolved design, time-sharing of circuitry resulted in extensive hardware savings. The IC's are incorporated functionally on 18 PC cards. The output of the logic in the Control Unit is used to drive dc motors coupled to the x-y table. Feedback is derived from phototransistors activated by disks on the x-y table; the resulting pulses are used to indicate a movement of 0.0001 inch along either axis of the table. The various counters are displayed on a CRT numeric generator or multiplexed into an electroluminescent readout.

Applications for the Numeric Control Unit commonly include drill presses, milling machines, and automatic welders, and will undoubtedly extend to uses other than mechanical positioning devices.

INTRODUCTION

With farsightedness and wisdom, the electronics industry is applying integrated circuits to more and more commercial products. Their use relieves the circuit designer from the details of designing and redesigning circuits and allows him more time for system considerations. The package designer can include more electronics in smaller, lighter weight packages than ever before. The product manager can increase his profit margin by having a more quickly produced product.

IC's are replacing analog circuits in many instances. One good example is a variable frequency oscillator. Another is a 40-watt audio amplifier that uses a highly efficient pulse modulation technique. RF, IF, and video amplifiers are being designed using linear IC circuitry. The change-over reveals these results: increased circuits reliability, repeatability, and decreased cost.

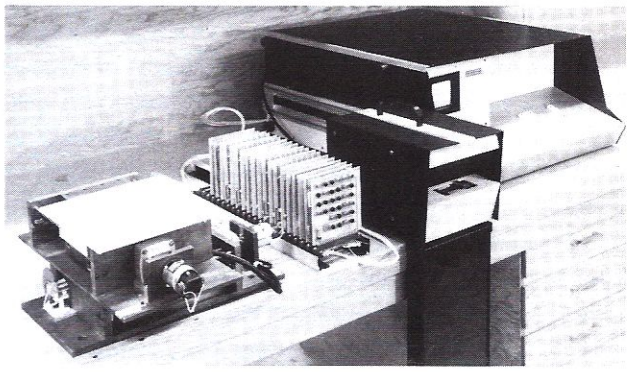

Fig. 1. Numeric controlled table system.

"Industrial control" implies decision making. An example of an industrial decision-making device is a Numeric Control Unit (Figure 1) to regulate an x-y table. The table could be used as a small drill press table. With little or no change in the logic circuitry, it could just as easily be a 3-ton milling machine or a 3-pound x-y plotter. While the end product of the described application is mechanical, the logic involved could just as well submit other outputs such as the number of gallons of fluid, yards of concrete, or number of automobiles.

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PURPOSE

Fairchild's decision to build an operating model of the Numeric Control Unit and x-y table was made for four reasons. First, technical problems could thus best be resolved. Since the electrical environment was presumed to be noisy, the question of solving contingent problems such as packaging could be studied. Second, the economics of using integrated circuits as opposed to other methods could be effectively compared. For example, the best way to accomplish the up/down counter function in a positioning device could be determined. It was ultimately found that recirculation of a BCD shift register storage element through a single add/subtract circuit (in cases of RTL counters beyond three digits) was more economical than straight BCD counting. Third, requirements for developing new integrated circuits or logic arrays could be studied. Dual function circuits, in addition to a 4-bit shift register and a binary-to-decimal converter, are being planned as a result of this and similar investigations. Fourth, a demonstrating model for marketing and sales of semiconductor products would be provided.

DESIGN GOALS

Certain design goals were established so that a system of sufficient complexity could be built. Basically, we wished to control movement in two directions (or axes) plus control of at least one auxiliary function—in this case, the up and down state of an ink pen. The motion control would be a result of information stored in some standard media such as a punched card, punched paper tape, or magnetic tape. Since system resolution and accuracy seemed to be governed solely by the mechanical end function, it was decided to build a small x-y table with a resolution down to 1/10 mil and a total travel of 4 inches on either of two axes.

These decisions then determined the 5-digit readout and the subsequent size of the various storage elements in the logic. To allow programming flexibility, two ways of commanding a distance would be developed: incremental and absolute. The first is defined as a dimension with respect to the preceding point; the second, as a dimension in respect to a pre-established reference point.

In addition, a programmable repeat capability to be used with incremental distances would be featured.

SYSTEM DESIGN GOALS

To be compatible with standards established on existing equipment (using discrete rather than IC's), the Numeric Control Unit was designed for punched paper tape inputs and a BCD code. The code follows a standard machine tool code established by E. I. A. *

*Character Codes for Numerical Machine Tool Controlled Perforated Tapes." RS244; July 1961.

The following format was selected for an axis movement. The axes characters would be either "X," – "Y" (x and y axes), or (A) (Auxiliary information). The movement mode would be a "P" for select absolute position, a "+" (forward or away from reference), or "-" (backward or toward reference), to select an incremental distance. Movement magnitude digits (from least to most significant) would be the next five characters.

In an incremental mode, the desirability of a number of repeats would be indicated by an "R." The number of the repeats would be the next five digits (from least to most significant). After programming both axes and auxiliary information, an "END OF BLOCK" character would be punched. The tape drive motor would then stop, and the logic would command the table motion. An "END OF RECORD" command would signal a stop of any further tape and machine action until a new start is manually initiated.

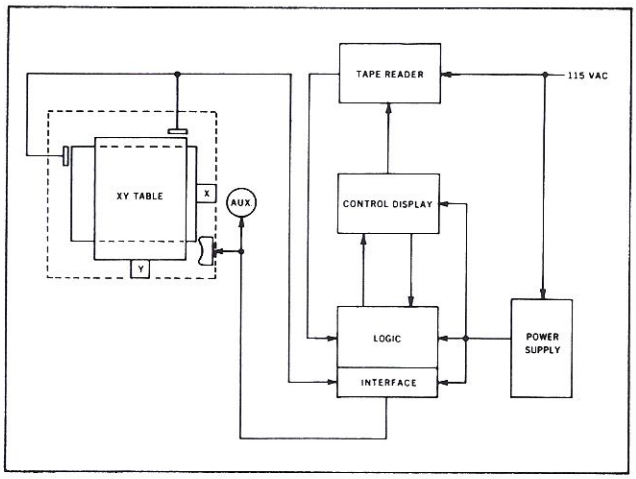


Fig. 2. System block diagram.

A block diagram of the Numeric Control Unit is shown in Figure 2. The first of the five blocks shown in the diagram is an x-y table that can be mechanically positioned in either of two axes by small dc motors. The auxiliary function, the pen, will contact the table surface or be removed on command. The tape stores a fixed series of movements which upon command will be completed mechanically by the x-y table. The control display allows the operator to position the table at any starting point, and will display information in various temporary memories within the logic. The logic and interface, the heart of the system, converts the tape reader information into discrete table movements. The logic circuitry accepts a feedback input from the table, determines position, signals for movement in either x or y direction, controls speed in any of the four discrete steps, and calls for information from the tape reader. The interface shifts the power level from IC level to dc for the drive motors or the auxiliary solenoid. The power supply can provide 3.6 volts at 10 amperes for the logic, 15 volts at

5 amperes for the dc motors, 28 volts at 0.5 ampere for the solenoid, and 150 volts at 0.1 ampere for the electroluminescent display.

LOGIC CONSIDERATIONS

As already noted, two modes of operation for the logic were established: incremental and absolute. If the incremental mode is used, the direction and magnitude of table movement must be programmed. In absolute mode, only the magnitude information for any given axis on the table needs to be programmed. The functional blocks necessary to accomplish movement will vary, depending upon which mode is selected. The simplest system for the incremental mode is shown in Figure 3.

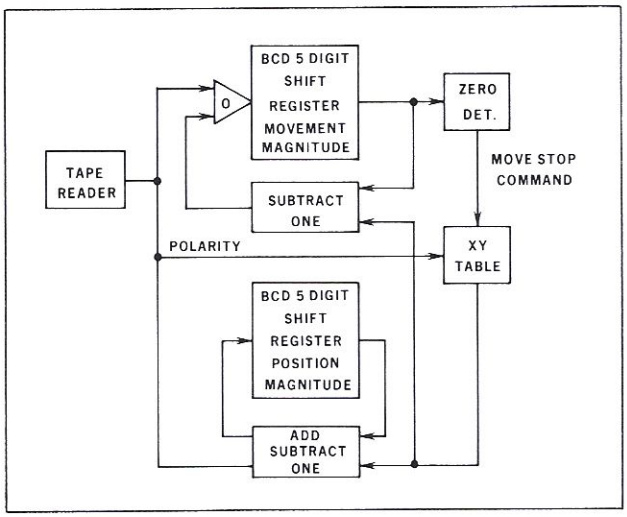


Fig. 3. Incremental system logic.

Here, the tape reader directly programs movement direction (polarity) and feeds the magnitude information into a 5-digit shift register (temporary storage). The information in the shift register is then interrogated by a zero detector. If any magnitude other than zero is detected, a "MOVE" command is generated and fed to the table motor, which starts table movement. Position pulses generated by the table transducer and fed back to the logic represent the mechanical resolution of the table, in that one pulse is generated for each detectable increment of linear table motion (0.0001 inch). The position pulses then begin to count down the information in the move magnitude register toward zero. They simultaneously count up (for positive movement) and store information in an up/down counter, formed by circulating the position magnitude shift register through an add/subtract-by-one circuit. This information is used to display continuously the position of the table. When zero is detected in the move magnitude register, a "STOP" command is generated and the table movement ceases.

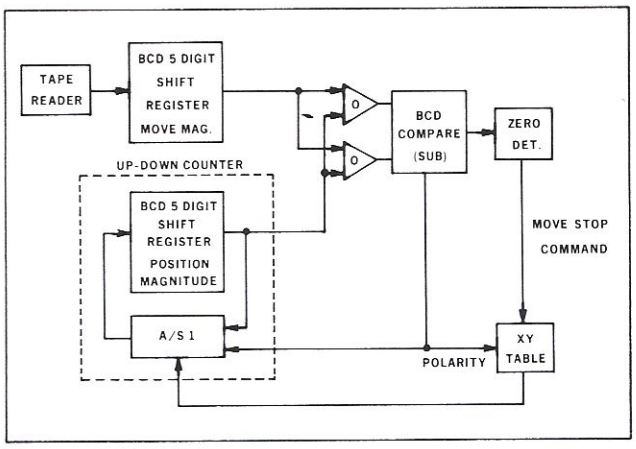


Fig. 4. Absolute position system logic.

The simplest system for absolute position is shown in Figure 4. In this system the tape reader will insert the magnitude information into a shift register as before, but now the information is compared with the information stored in the position up/down counter. If the information is not identical, the difference will be something other than zero. After sampling this difference, the zero detector circuit will generate a "MOVE" command. The fact that one magnitude is greater than the other would also be determined within the comparator and used to generate direction of movement (polarity) commands. As the table moves, position pulses are created. This time, however, the pulses are used only to increase (positive movement) or to decrease (negative movement) the position up/down counter. When counter value is the same as that initially stored in the register, comparison occurs, and the zero detector will generate a "STOP" command. BCD comparison may be obtained by using the full BCD subtract circuit, the output of which will be the difference between the two inputs. Either mode requires approximately the same amount of hardware which must be multiplied (except for the tape reader) for each axis in which numerically controlled movement is desired.

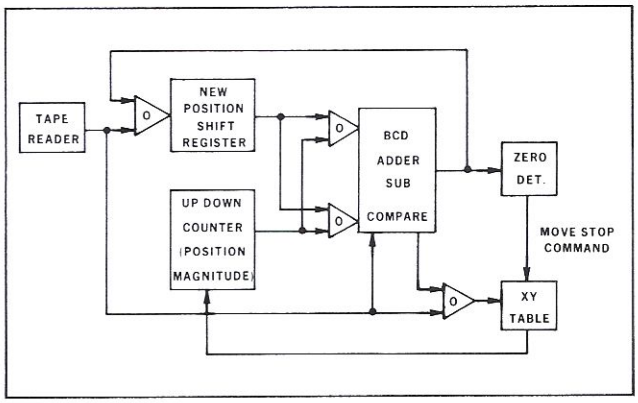


Fig. 5a. Incremental converted to absolute position.

Since both modes of operation were desirable, it simply became a question of selecting which one of the systems to modify for this particular application (Figures 5A and 5B).

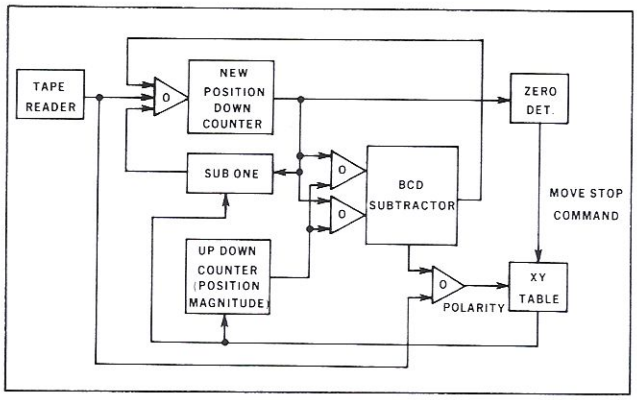


Fig. 5b. Absolute position converted to incremental.

In Figure 5A, incremental information must be converted to absolute position information by either adding or subtracting (depending upon programmed polarity), the information contained in the "up/down position counter" to the information contained in the "new position shift register." Then, the BCD adder/subtractor (A/S) output is re-stored in the new position register. The BCD A/S becomes a comparator and the system resumes the operation described previously. (Figure 4). In this case, the additional hardware needed to accomplish the desired modification would be the full BCD adder/subtractor and the essential control circuitry for each axis to be controlled.

In Figure 5B, absolute position information is converted to incremental by subtracting the "up/down position counter" magnitude from the "new position magnitude" (positive movement) or the new position magnitude" from the "up/down position counter" magnitude (negative movement). The difference will be the desired incremental information which is then stored and handled as described (Figure 3).

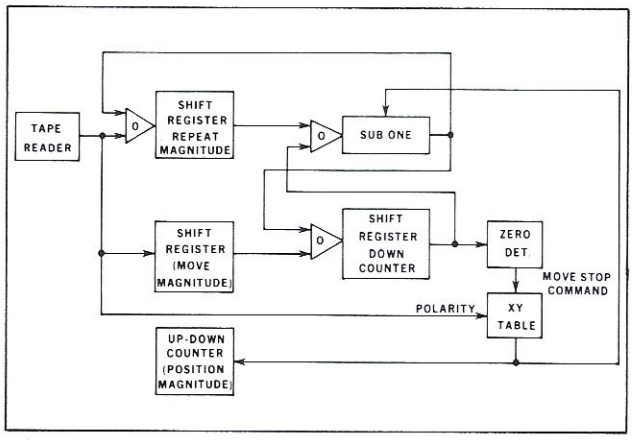


Fig. 6. Repeat feature for system logic.

The additional hardware needed would be the BCD subtractor and the control circuitry; however, here the BCD subtractor may be time-shared with the other axis to be controlled. To enhance our program flexibility, a repeat function would be used with the incremental mode of operation (see Figure 6).

To accomplish repeat operation with an incremental scheme, two additional shift registers plus the controlling circuitry are required—one register to store the movement magnitude for as long as it is needed; the second register to store the programmed number of repeats. The subtract-one circuit may be used to count down the repeat shift register magnitude with each machine cycle. The zero detector may also be time-shared to indicate no further repeats (repeat register zero) or no further movement (down counter register zero).

The block diagram of the final system for one axis only is shown in Figure 7. The time-sharing possibilities and the repeat feature made our choice obvious. All blocks must be repeated for each axis to be controlled, except for the tape reader and the full BCD subtractor.

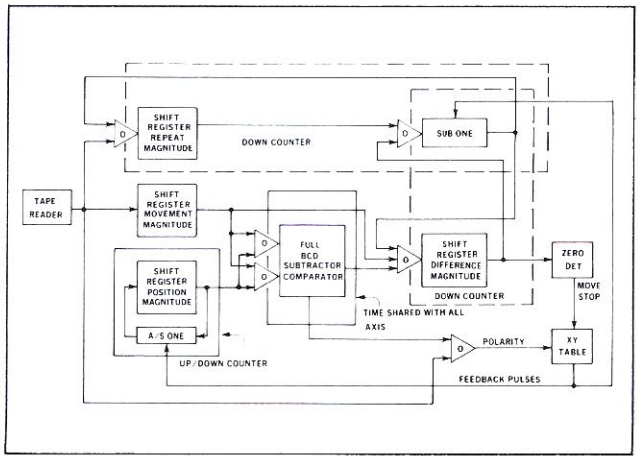


Fig. 7. System logic block diagram.

CIRCUIT BLOCKS

A clock consisting of 1/2 a μL9927 (Figure 8) provides the basic timing needed in the serial operation of the system.[1] The clock in turn drives a modulo five counter[2] as well as the shift registers throughout the system. The outputs of the modulo five counter are decoded by μL9914's, generating time signals to correspond to each of the significant digits in our system.

Since the basic clock frequency is 1 megahertz, it is seen that one 5-digit cycle will require 5 microseconds. If we

[1] Fairchild Application Note 106.

[2] Fairchild Application Note 120.

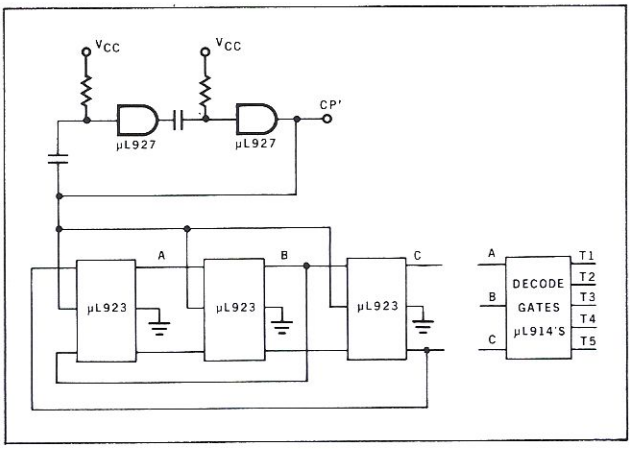


Fig. 8. System timing.

assume a table speed of 1 inch per second, the position pulse frequency would be 10 KC; with a speed of 2 inches per second, one position pulse every 50 microseconds would result; etc. This means that, with the x-y table, the inherent speed of the logic is much faster than the maximum speed of the table.

This allows a serial approach in this system, permitting a considerable hardware savings. For example, a shift register and the add/subtract-one circuit in a count up/count down scheme uses less hardware than a series of bidirectional decade counters.

The logic portion of this system was implemented using various RTL Micrologic® integrated circuits. Specifically, these were μL9900's (clock drivers), μL9914's dual input gates, μL9923's (JK flip-flops), μL9915's (triple input gate), μL9926's (JK flip-flops) and μL9927's (quad inverters). The majority of these were the first three mentioned, the reason being that these three IC's are less expensive devices.

An examination of the overall logic system block diagram will indicate that several function blocks are used repeatedly. Most common among these is the 5-digit BCD shift

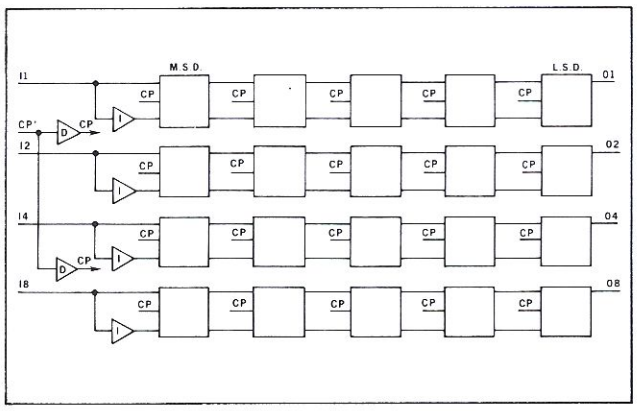


Fig. 9. 5 - digit shift register.

register (Figure 9). The register, which is the basic memory in the system, is comprised of twenty shift register elements (JK flip-flops; four per digit) plus four

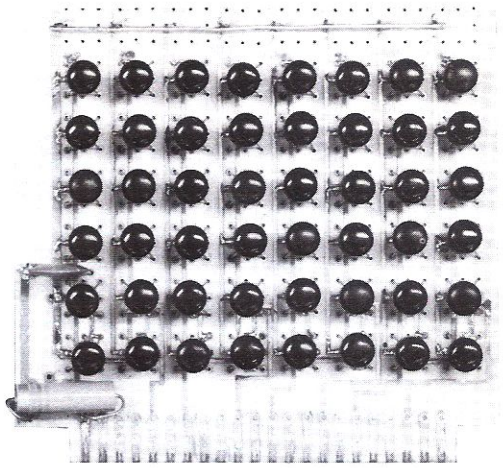


Fig. 10. Board #7.

input inverters and two clock drivers. The BCD unit accepts input information that is parallel by bit and serial by digit, and shifts the information towards the output with each negative-going transistion of the clock pulse. The logic system requires five digits, but can be expanded to accommodate any number of digits by adding four JK flip-flops per digit within the register. These could be replaced in blocks of four by the 4-bit shift register element (μL9997).

Two complete BCD shift registers are mounted on one 4.5-by-5 inch PC board (Figure 10)

BCD subtraction is accomplished using a well-known Boolean method; i.e., the subtrahends complement plus-one is added to the minuend to obtain the difference. In the subtract-by-one circuit, the complement of binary one

TABLE 1.
BCD SUBTRACT-BY-ONE.

1001 (Binary 9) 1111 (Binary 15) 1-1000 (Binary 8 plus carry)	0100 1111 1-0011 (Binary 3 plus carry)
1000 (Binary 8) 1111 1-0111 (Binary 7 plus carry)	0011 1111 1-0010 (Binary 2 plus carry)
0111 1111 1-0110 (Binary 6 plus carry)	0010 1111 1-0001 (Binary 1 plus carry)
0110 1111 1-0101 (Binary 5 plus carry)	0001 1111 1-0000 (Binary 0 plus carry)
0101 1111 1-0100 (Binary 4 plus carry)	0000 1111 1111 (Binary 15 no carry)

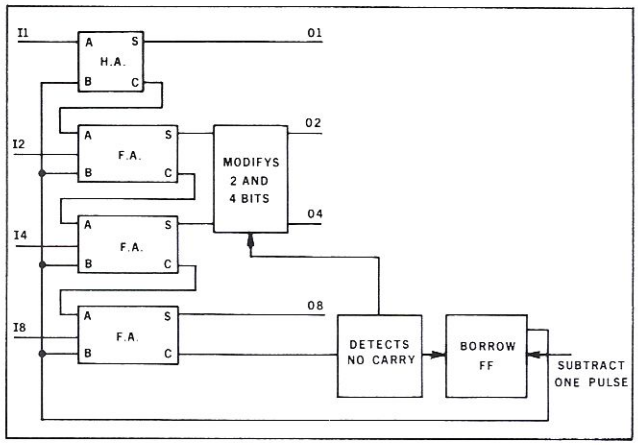


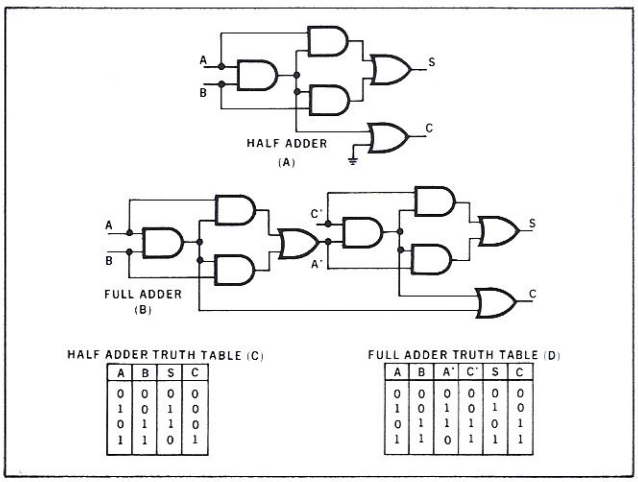
Fig. 11. BCD subtract-by-one circuit.

(binary 14) plus-one (binary 15) is used to obtain the subtraction-by-one. The results of the subtract-by-one circuit is best explained by observing what happens when binary 15 is added to another binary number, as shown in Table 1.

In all cases except zero, the result is a subtract-by-one plus a carry. In the case of zero, the result is binary 15 and no carry. The circuit (Figure 11) detects the lack of a carry and modifies the two and four binary weights to the logical zero condition to produce a binary nine in the output. Simultaneously, a borrow flip-flop is set which subtracts one from the next higher order BCD digit.

To initiate a subtract-by-one operation, a pulse is applied at the start to preset the borrow flip-flop.

The half-adder and full-adder circuits indicated in Figure 11 are μL9914's arranged in an "exclusive or" configuration. The half adder and full adder are basic building blocks used in the subtract-by-one, the add/subtract-by-one and the full BCD subtractor. The circuit and truth tables for each are shown in Figure 12.



A	B	S	C
0	0	0	0
1	0	1	0
0	1	1	0
1	1	0	1

A	B	A'	C'	S	C
0	0	0	0	0	0
1	0	1	0	1	0
0	1	1	0	1	0
1	1	0	1	0	1

Fig. 12. Adder logic.

The add/subtract-by-one circuit (Figure 13) is only a little more complicated than the subtract-by-one circuit. In the subtract mode, its operation is identical with that of the subtract-by-one circuit. In the add mode, however, the binary scheme changes slightly. Adding binary one will result in the next higher binary number in all cases.

In a BCD mode, however, when one is added to nine, the result will be the required binary zero plus a carry instead of the binary ten. The circuit will detect the presence of the eight and the two weights and will modify the output to 0000. Simultaneously, the carry flip-flop is set and adds one to the next higher order digit. Again, to initiate the add or subtract-one operation, a pulse is applied at the

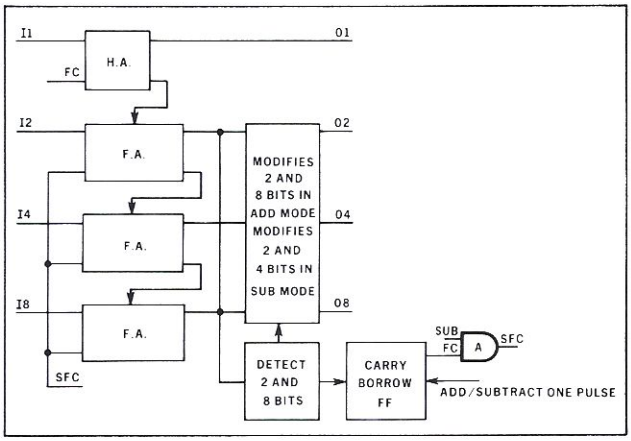


Fig. 13. BCD add/subtract-by-one circuit.

start to preset the carry flip-flop. Micrologic ® integrated circuits μL9914's and μL9923's were used to implement this circuit.

Full BCD subtraction is shown in Table 2.

TABLE II.

FULL BCD SUBTRACTION.

1001	(Binary 9)
1101	(Binary 2 complement)
1-0110	(Binary 6 plus carry)
0001	(Binary 1)
1-0111	(Binary 7 plus carry)
0110	(Binary 6)
1011	(Binary 4 complement)
1-0001	(Binary 1 plus carry)
0001	(Binary 1)
1-0010	(Binary 2 plus carry)
0100	(Binary 4)
1001	(Binary 6 complement)
1101	(Binary 11 no carry)
0001	(Binary 1)
1110	(Binary 14 no carry)
1010	(Binary 10 Mod factor)
1-1000	(Binary 8)
0110	(Binary 6)
0110	(Binary 9 complement)
1100	(Binary 12 no carry)
0001	(Binary 1)
1101	(Binary 13 no carry)
1010	(Binary 10 Mod factor)
1-0111	(Binary 7)

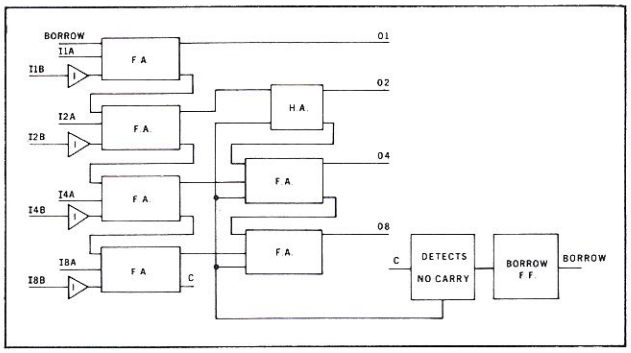


Fig. 14. Full BCD subtractor circuit.

In all cases, a "CARRY" is normally generated except when the minuend is less than the subtrahend, where the difference results in a number that is ten less than the desired result and has no carry. Therefore, the BCD circuit (Figure 14) detects the lack of a carry and modifies the output by adding binary ten. A borrow flip-flop is

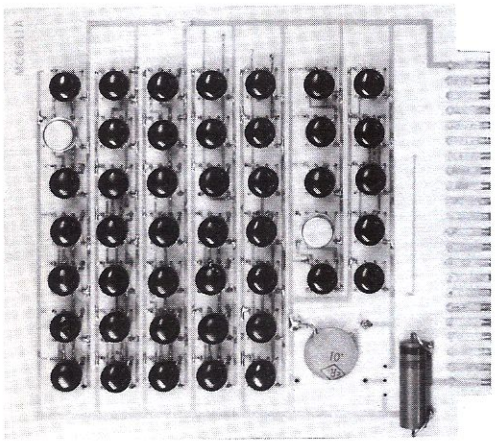


Fig. 15. Board #12.

simultaneously set and will subtract one from the next higher order digit. Except for one μL9926 (used as the borrow flip-flop) and one μL9927 (used as the input inverter), μL9914's were used exclusively. The inverters

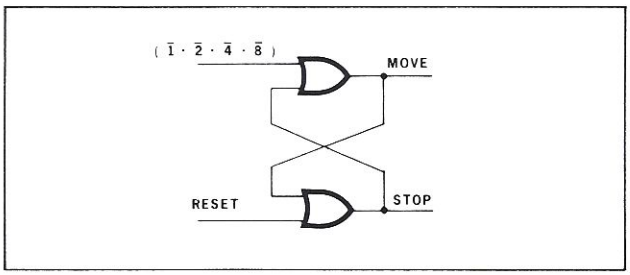


Fig. 16. Zero detector.

perform the desired complementing of the subtrahend. Figure 15 is a photograph of the full BCD subtractor circuitry on one card.

The zero detector is a μL9914, cross-coupled to form a set-reset flip-flop (Figure 16). The detector is reset just prior to each machine cycle and the set side interrogates the register output for the essential time period.

If anything other than zero appears, the flip-flop is set to indicate "NO ZERO." If a zero appears, the flip-flop remains in the reset condition, indicating that the BCD numbers in the register are at zero. Various speeds may be selected as a function of the distance to be travelled, as given in the following examples.

Distance	Speed
00000	Stop
00000 to 00009	Slow
00009 to 00099	Medium
00099 to 99999	Fast

HARDWARE CONSIDERATIONS

The various circuits were incorporated on 4.5-by-5.0 inch printed circuit cards. The number of IC's per card varies from 20 to 48. There is a total of eighteen cards in the logic portion: four are for timing and control, the fifth one is the speed flip-flops for both axes, the sixth one contains multiplexing gates for the x-axis move magnitude and repeat magnitude shift register. The seventh one is the x-move magnitude and repeat magnitude shift register. The eighth one contains the subtract-one circuit and associated multiplexing circuitry. The ninth one is the difference and counter shift register. The tenth one is the add/subtract-one circuit. The eleventh one is the multiplexing for the full BCD subtractor, the twelfth card. The thirteenth through seventeenth cards are the same as the sixth through the tenth, except for the y axis. The eighteenth board is interfacing to the x-y table.

The x-y table (Figure 17) built for the project has a total travel range of 3.9999 inches in either of two axes. Two safety limit switches on each axis prevent damage to the mechanical drive system if the table exceeds its normal range. Each axis is driven by a small dc motor rated at 12 volts and 2 amperes. A small disk, with ten evenly spaced holes around the perimeter, is driven from the mechanical linkage. The spacing between each hole represents 0.0001 inch of linear table movement. Position pulses are generated as a result of the holes, allowing a light path to energize a phototransistor (Fairchild FPM100), which in turn directly drives the gates.

A CRT numeric character generator may be used to display the various shift register contents or two 5-digit electroluminescent readouts may be used to display the magnitudes

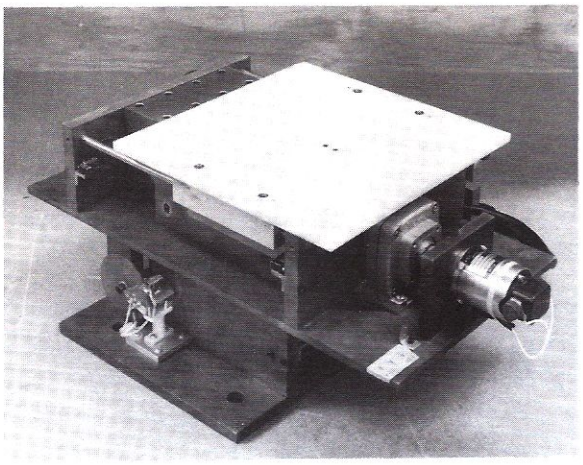


Fig. 17. X-Y table.

associated with each axis. Controlling each readout is a four-position switch that will select any one of the four registers associated with a given axis. A pair of indicator lamps will show when the table travel limits have been exceeded.

The following controls are also available. The tape reader has a toggle switch to select manual or automatic operation. In manual mode, tape movement can be one step at a time or a series of steps (by holding the switch down).

The table is controlled by toggle switches, with a selection of manual or automatic mode; forward or reverse direction; and fast or slow speed; the last two being a function of the first in the manual mode. The logic system is controlled by three push buttons: one for START, one for STOP, and one for COUNTER RESET.

CONCLUSIONS

The Numeric Control Unit (Figure 18) is a basic building block with the capability of accepting standard format information and transforming it into mechanical movement. With a little imagination, it is apparent that the auxiliary function could be either a scribe, a drill head, a milling head, or even a sewing head. If necessary, the axis as well as the auxiliary function can be expanded into more functions or directions.

Although this system has been implemented using the RTL family of micrologic, it could have been as easily fabricated using the newer DTL or TTL families. In fact with the use of the "wired on" configuration and the added complexity in the new Dual-in-Line* package some reductions in device count would have been possible.

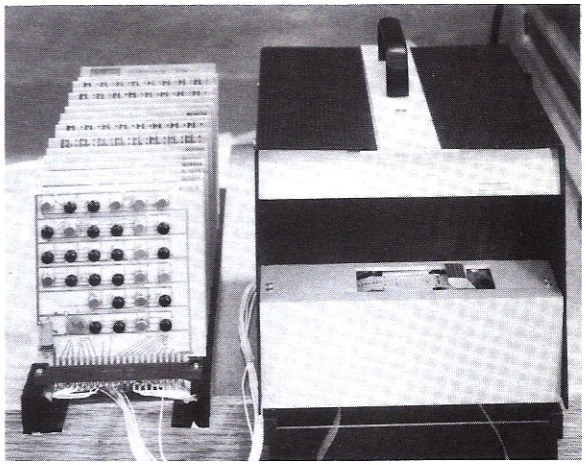


Fig. 18. System logic and tape reader.

*Fairchild patent pending.